(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 October 2002 (24.10.2002)

PCT

(10) International Publication Number
WO 02/084337 A2

(51) International Patent Classification[7]: G02B

(21) International Application Number: PCT/US02/08251

(22) International Filing Date: 10 April 2002 (10.04.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/283,017 11 April 2001 (11.04.2001) US

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(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

WO 02/084337 A2

(54) Title: POLARIZATION TO PHASE CONVERTER

(57) Abstract: The invention provides an apparatus and method for time delaying different polarization components of a signal relative to one another, comprising a polarization signal splitter which splits first and second polarization components of an input signal into a first component signal and a second component signal such that said first component signal propagates along a first path and the second component signal propagates along a second path, wherein said first component signal reaches a location relative to when said second component reaches said location at times differing by a delayed time, and use of the apparatus in a communication system. The apparatus may be used for quantum cryptography, to convert a sender's polarization-qubit signal into a signal appropriate for channels and receivers based on phase-encoded schemes.

weak optical signals, ideally single photon states, are sent from the sender Alice to the receiver Bob [C. H. Bennett and G. Brassard, IBM Technical Disclosure Bulletin 28, 3153 (1985)]. A sufficient choice for the four polarization directions might be the set of right and left circularly polarized light fields plus the set of linearly polarized light fields making angles ±45° with respect to the horizontal and vertical. (Note that optical polarizations in uniform media are normally defined with respect to the propagation direction of the light and the plane perpendicular to that direction. The horizontal and vertical directions lie in that perpendicular plane.) These four polarization vectors can be written in a compact form in terms of a phase difference between horizontal and vertical polarization directions, $\vec{h}$ and $\vec{v}$, as $\vec{\varepsilon}(\theta) = \vec{h} + e^{i\theta}\vec{v}$, where $\theta = -\pi/2,\ \pi/2,\ 0$, and π for right circular, left circular, 45° linear, and –45° linear polarizations, respectively. Thus, the information in a polarization-based signal is uniquely given by this phase θ. In quantum cryptography, Alice makes a random choice of the polarization of her signal, while Bob selects a polarization basis at random for detection. The process allows for the distillation of a secure quantum key. Crucially, Alice and Bob have devices designed to send and process only the quantum information contained in the polarization of the light signals.

In the phase category of quantum key distribution, Alice encodes the quantum information in the random phase of a signal she sends to Bob [C. Bennett, PTO/US5307410; P. D. Townsend, J. G. Rarity, and P. R. Tapster, Elect Lett 29, 1291 (1993); A. Ekert et al., "Quantum Cryptography", in D. Bouwmeester, A. Ekert, A. Zeilinger, The Physics of Quantum Information, Springer-Verlag, Berlin, p. 32 (2000)]. Using an interferometer with unequal path lengths and an input field pulse envelope $E \sim f(t)$ in time, Alice creates an outgoing electromagnetic field signal of the form $E(t) \sim \left(f(t-\tau) + e^{i\theta} f(t)\right)/\sqrt{2}$, where θ is the relative phase difference between outgoing field pulses that is imposed by an (active) phase modulator in one of the interferometer paths, and τ is the time delay of one of the

PCT publication WO 9744936, naming Townsend as inventor, discloses a phase-based quantum cryptography scheme.

W. Tittel, G. Ribordy, and N. Gisin, Quantum Cryptography, Physics World 3, 41 (1998) discloses how to avoid instability of separated interferometers.

US patent 5,768,378 to Townsend discloses employing quantum cryptography in a passive network environment.

US patent 6,028,935 to Rarity et al. discloses a passive quantum cryptographic detector set-up.

The teachings of N. Gisin et al., http://xxx.lanl.gov/abs/quant-ph/0101098, are hereby incorporated by reference.

The present inventors realized that polarization signals coupled to a transmission channel may require active stabilization control owing to polarization rotations through optical elements, birefringence, polarization mode dispersion, and thermal and mechanical fluctuations.

The present inventors realized that a sender may want to create deterministic or random polarization-based signals, while the receiver may want to receive a phase-encoded signal. The present invention provides this capability by allowing polarization-based signals to be converted into phase-encoded signals for transmission and/or reception. By assuming a polarization-based signal is what is input into a system of the present invention, the system also eliminates the active phase modulation required for phase-based senders.

signal and a second component signal such that said first component signal propagates along a first path and the second component signal propagates along a second path, wherein said first component signal reaches a location relative to when said second component reaches said location at times differing by a delayed time; and a receiver for coherently receiving said first component signal and said second component signal, thereby generating a coherence signal representative of said input signal.

With reference to a specific embodiment, these and other objects of the invention are provided by systems, such as shown in Fig. 1, that map the phase θ (which defines information by state of polarization, a polarization-based information signal) into the informational phase θ of a phase-based scheme (in other words, a time delay scheme). Thus, the invention allows polarization-based signals in quantum cryptography to be converted into phase-encoded signals for transmission and/or reception.

In accordance with the system and method of the present invention, an input signal consists of an electromagnetic field pulse or a sequence of field pulses in one or a combination of a number of possible polarization directions or states. The input signal of the invention thus constitutes an input signal encoded with information in the polarization degree of freedom.

The system of the invention uses a polarization dependent signal splitter to split an input signal into two components each of which then propagates along a different path. The polarizations of the two input components are substantially (to the extent provided by the polarization dependent signal splitter) orthogonal to one another.

The splitter sends a first component of the input field into the first path and a second component into the second path. Note that only the polarizations of the two input components need to be substantially orthogonal. The polarizations of the two output paths can have any specific relationship, provided that the users know this

The output of the system constitutes a phase-encoded signal and may be coupled to any suitable transmission medium for transmission to a receiver.

Preferably, the input signal which contains the information to be encoded and transmitted is time sequenced to another easily detectable signal, a time sequencing signal, to facilitate the receiver's determining when information is being received. The time sequencing signal may be transmitted in a separate medium from the input signal. This has been described in Bennett US Patent 5,307,410.

Another possibility is to send the time sequencing signal simultaneously with the information signal in the same medium. For example, the time sequence signal can be at a wavelength different from the information signal, or it may be a signal of any wavelength transmitted a predetermined time in advance or after the information signal. Wavelength division multiplexing can be employed by combining the signals from the quantum channel, timing channel, and a public channel into a common medium, as described in Townsend US Patent 5,675,648.

The encoding provided by the present system is effective for all input signal polarizations signal strengths for a coherent input signal. Thus, this system enables transmission of information using very low intensity information input signals The coherent input signals may be of any statistical type: classical states of the field, states with large average photon numbers, weak or strong coherent states, single photon states, or other quantum states, as long as the information of importance is initially encoded in the polarization. Moreover, the system may include attenuators located to attenuate either the input or output intensity to a desired signal level.

The output signal may be transmitted through either a polarization-preserving or a non-polarization-preserving medium; optical fibers in the case of the preferred embodiment shown in Fig. 1. The relative phase between time-separated output signals from the system of the present invention remains essentially unchanged by the properties of the transmission medium through with the output signal travels, since both components of the output signal experience the same

phase-based quantum cryptography scheme disclosed in WO 9744936 could be modified to include the system of the present invention

Another example of a quantum key generation system of this invention is a combination of the phase-based receiving interferometer for quantum cryptography disclosed in BB84 combined with a polarization-based sender system, such as that shown in Fig. 1.

DESCRIPTION OF THE FIGURES

Fig. 1is a schematic of the apparatus embodying the present invention;

Fig. 2 is a schematic showing structure of the present invention in a quantum cryptography transmission detection system;

Fig. 3 is a table showing relationships between a sender's polarization qubits, a receiver's phase-based measurement, and quantum cryptographic bits element 203 of Fig. 2; and

Fig. 4 shows a purely phase-encoded quantum cryptography communication system.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 shows system 20, wave or light pulse paths, and a coordinate system. System 20 includes polarizing beam splitter 2, half wave plate 3, polarizer 4, beam splitter 5, phase shifter 6, polarizer 7, half wave plate 8, mirror 9, 10. Waves are shown along paths 1, 11, 12, 13, 14, and 15. Y-Z coordinate system is shown at 16.

System 20 is configured so that polarizing beam splitter 2 splits input light signals propagating along path 1 into two signals. A first split signal propagates along path 11 such that a portion of that split signal passes through half wave plate 3, polarizer 4, and beam splitter 5. A second split signal propagates initially along path 12, is substantially reflected by mirrors 10, 11, and part of that reflected signal propagates through half wave plate 8, polarizer 7, phase shifter 6, and is reflected by beam splitter 5. The portions of the first and second split signals that propagate

embodiments include radio wave, microwave, far infrared, infrared, visible, and ultraviolet.

In operation of system 20, light propagate in the (y-z) plane of the page in Fig. 1. As a result, S-polarization (i.e., polarization directed in the plane of incidence) for the input signal lies along the y-direction, and P-polarization (i.e., polarization perpendicular to the plane of incidence) is directed along the x-direction (which is into the page in Fig. 1). These polarization states are also called (H)orizontal and (V)ertical, and shown as such along paths 11, 12. Each input signal propagating along the z-direction is typically polarized in one of four polarization, right circular, left circular, plus 45 degrees, and minus 45 degrees.

The theory of the operation of system 20 can be described using polarization vector and a state ket in the transverse direction of the single photon Hilbert space or classical states of a polarized field. The input-output transformations of the photon creation operators corresponding to the set-up of Fig. 1 can be constructed to apply to any input state of the field. For the single photon of the preferred embodiment, coherent superpositions of the horizontally and vertically polarized input operators then lead directly to the state transformations and possible output states that follow.

The input creation operators relevant to the present invention create single photon modes from the vacuum with four different polarizations. , K.J. Blow, R. Loudon, and S. J. Phoenix, Phys Rev A 42, 4102 (1990) describes a theory of field quantization using pulsed continuum modes propagating in a straight line. Extending this theory, we can define these operators heuristically in their rest frame as $b_R^\dagger(t)$, $b_L^\dagger(t)$, $b_{45^\circ}^\dagger(t)$, and $b_{-45^\circ}^\dagger(t)$. They operate on the vacuum to create single photon field pulses of a desired shape traveling toward the input port in Fig. 1 with right circular, left circular, linear polarization at 45° in the x-y plane, and linear polarization at -45° in the x-y plane, respectively. Parenthetically, the eigenstates of the corresponding annihilation operators are continuum coherent states with a well-defined photon flux and photon number, which may be relevant to other

The operator transformations above are general. The preferred embodiment essentially describes their action on the vacuum to create the single photon input modes and the corresponding output modes. The input creation operators (0.2)-(0.5) create the following input kets from the vacuum, $|j\rangle = (|H\rangle + e^{i\theta_j}|V\rangle)/\sqrt{2}$. In the circular basis, the input field polarization could be in one of the two orthogonal states, right circular

$$|R\rangle = (|H\rangle - i|V\rangle)/\sqrt{2} \tag{0.10}$$

and left circular

$$|L\rangle = (|H\rangle + i|V\rangle)/\sqrt{2}. \tag{0.11}$$

In a linear 45° basis, the input field polarization could be in one of two other states orthogonal to one another,

$$|45^\circ\rangle = (|H\rangle + |V\rangle)/\sqrt{2} \tag{0.12}$$

and

$$|-45^\circ\rangle = (|H\rangle - |V\rangle)/\sqrt{2}. \tag{0.13}$$

The states from the linear 45° basis are not orthogonal to the circular basis, and each state ket's time-dependence as a pulse that travels into the PBS is suppressed in the notation for now. These single photon states might be launched into the PBS one at a time.

All optical components necessary to implement system 20 are available from Optics for Research, Oriel, Meadowlark Optics or other quality optical component sellers. The orthogonal eigenmodes of the Polarizing Beam Splitter (PBS) 2 are set to be the linear basis set, $|H\rangle$ and $|V\rangle$. The former is reflected into path 13, while the latter is transmitted into path 11. All of the circular and linear 45° basis states have projection amplitudes onto PBS 2 bases that are equal in magnitude but different in phase, and therefore the exit states of the PBS 2 after a circular or linear 45° input state are distinct for each input state. In fact, the relative phase θ_j (0.1) between $|H\rangle$ and $|V\rangle$ for each of the input states of equations (0.10)-(0.13) uniquely identifies the input state and will become the relative phase difference between time-separated

by the half wave plate 3 and guaranteed to be in a defined polarization by polarizer 4.

If the signal traversing paths 12, 13, 14 reaches beam splitter 5 still polarized along the y-direction as $|V\rangle$, then half wave plate 3 and polarizer 4 are unnecessary. Otherwise, they could be used either to correct for unintended polarization rotations occurring in the signal traversing paths 12,13, 14, or to align the polarization at beam splitter 5 to a polarization other than $|V\rangle$.

Moreover, the signals on paths 11 and 12, 13, 14 may acquire a relative phase ψ with respect to one another during propagation. If desired, phase shifter 6 or other phase compensator could be used to correct this residual phase difference between the two paths to isolate the relative phase difference θ_j of importance. Beam splitter 5 is substantially polarization insensitive, and preferably a 50-50 beam splitter. At the spatial point where the two paths meet, the polarizations and spatial modes from each path must overlap, even though the signal along one path is delayed temporally.

The target polarization at BS shown in Fig. 1 is set to S-polarization. However, the exact polarization at beam splitter 5 is unimportant.

Optical components in Fig. 1 such as P1, HWP2, P2, and PS are compensating components that are unnecessary in principle but are useful in practice to guarantee the conditions for mode overlap of the signals propagating on path 11, and paths 12, 13, 14, when they exit along path 15.

Spatial filters or other optical components, which do not appear in Fig. 1, may be used to align the spatial modes and polarizations at BS. Similarly, the optical delay lines defined by paths 11, and 12, 13, 14 can be formed from any medium, which may eliminate the need for some of the components shown in Fig 1. For example, use of optical fiber may moot the mirrors 10, 9, but then require fiber optic couplers to couple signals into or out of the fiber.

After output, the state can propagate through a birefringent medium and/or quantum channel, such as an optical fiber or atmospheric disturbance, and maintain its fidelity. (Here, we are ignoring other loss mechanisms and assume the channel medium response is identical for each of the separated pulses.) Polarization rotations affect each component of the field in the same way now, preserving the relative phase and thus the information from the original polarization encoding.

For example, in quantum cryptography, this preferred embodiment can be used to transform a sender's polarization qubits into a phase-encoded scheme that feeds directly into a receiver's measurement interferometer after propagation along a (quantum) transmission channel between sender and receiver. In this case, the optical delay between the two paths in system 20 can be seen in some sense as the sender's half of an interferometer. Thus, the present invention's optical delay line and path lengths preferably are stabilized with respect to a receiver's delay line, for interferometric stability. For this purpose, air gaps or other passive or active means may be useful. Moreover, combinations of stacked quarter-half-quarter wave plates may be used to stabilize the polarization in various optical schemes. See, for example, N. Gisin et al., http://xxx.lanl.gov/abs/quant-ph/0101098.

Fig. 2 shows use in quantum cryptography, a schematic of a system disclosed in BB84, but in which system 20 has been included.

Fig. 3 shows the possible quantum cryptographic bits for the system of Fig. 2.

Fig. 2 shows a sending unit 201, system 20 as described in Fig. 1, a transmission channel 210, and receiver 205.

In Fig 2., sending unit 201 generates input pulses having an input polarization and that propagate along path 202. The system is designed so that the input pulses are received and processed by system 20. System 20 transmits an output signal along transmission channel 210. Receiver 205 receives and processes the transmitted signal. Receiver 205 preferably includes an interferometer including

These ideas are summarized in Fig. 3, where the sign in the possible interference signal applies to detection events in the constructive D1 (+) or destructive D0 (–) output ports of the receiver's final beam splitter.

Fig. 4 herein is a reproduction of Fig. 4 in WO 9744936. Fig. 4 herein shows in transmission and encoding system 410, transmission region 420, and detection and decoding region 430. The apparatus shown in of Fig. 4 in WO 9744936 could be modified to employ the present invention by replacing elements labeled 1-6 in Fig. 4 in WO 9744936, shown as element 410 herein, i.e., up to the output of the sending interferometer, and inserting elements of system 20 in their place. Fig. 4 is exemplary of how the system 20 of the present invention may be employed with existing communication systems.

In another embodiment of the present invention, the present invention converts polarization to phase information for optical signals of arbitrary intensity from a coherent source, such as a laser. Such a device operates with same apparatus as the preferred embodiment, as shown in Fig. 1.

In another embodiment of the present invention, optical signals are attenuated to consist of dim coherent state pulses (from laser pulses, for example). The attenuation may occur immediately before the input signal reaches the polarizing beam splitter 2 and/or immediately after the output signal leaves beam splitter 5 of Fig. 1. Otherwise, the device operates with same apparatus as in the preferred embodiment. For example, a phase-based quantum cryptography scheme disclosed in WO 9744936, naming Paul Townsend as inventor could be modified to include a polarization-based sending unit and system 20 of Fig. 1, as discussed with respect to Fig. 4 herein. Fig 4 could be modified to include a polarization-based sender and system 20 of Fig. 1. Townsend's Fig. 4 system could be modified by replacing the elements labeled 1-6 with a polarization-based sending unit and system 20 of Fig. 1. Thus, the system and method of the present invention may be inserted into pre-existing communication systems to improve those systems.

embodiment may be relevant to so-called strong reference pulse schemes of quantum cryptography, which are discussed in C. H. Bennett, Phys Rev Lett 68, 3121 (1992). The complex reflection and transmission coefficients of BS are taken as **r** and **t**, respectively, in this embodiment. Then, the operator transformations described in equations (0.6)-(0.9) are replaced by:

$$b_R^\dagger(t) \to d_R^\dagger(t) = \left(\mathrm{r} b_V^\dagger(t-\tau) - i\mathrm{t} b_V^\dagger(t)\right)/\sqrt{2} \qquad (0.18)$$

$$b_L^\dagger(t) \to d_L^\dagger(t) = \left(\mathrm{r} b_V^\dagger(t-\tau) + i\mathrm{t} b_V^\dagger(t)\right)/\sqrt{2} \qquad (0.19)$$

$$b_{45^\circ}^\dagger \to d_{45^\circ}^\dagger(t) = \left(\mathrm{r} b_V^\dagger(t-\tau) + \mathrm{t} b_V^\dagger(t)\right)/\sqrt{2} \qquad (0.20)$$

$$b_{-45^\circ}^\dagger \to d_{-45^\circ}^\dagger(t) = \left(\mathrm{r} b_V^\dagger(t-\tau) - \mathrm{t} b_V^\dagger(t)\right)/\sqrt{2} \qquad (0.21)$$

The relative phase between the time-separated components is still determined only by the input polarization state.

In another embodiment, the previously unused output port of beam splitter 5 in Fig. 1 may be used either to act as another phase-encoded source in conjunction with the main output port or to monitor errors or other information in the transmission and reception of the output signal of the preferred embodiment. For a true single photon source in quantum cryptography, a detection event at the receiver end that triggers the recording of a zero or a one should not coincide with a detection event on the previously unused BS output port. The apparatus for this embodiment is identical to that of the preferred embodiment.

In another embodiment, the signals that combine on beam splitter 5 in Fig. 1 from path 11 and path 12, 13, 14 need not be in the same polarization state. The outgoing signal may then contain two pulses, separated in time by τ with the original polarization information still encoded as the relative phase between pulses. However, the polarization state of the two output pulses themselves can be arbitrary with respect to one another by adjustment of the wave plates and polarizers in system 20 of Fig. 1. This embodiment pertains to classical and quantum electromagnetic signals of arbitrary strength. While this embodiment may not

I Claim:

1. An apparatus for time delaying different polarization components of a signal relative to one another, comprising:

a polarization signal splitter which splits first and second polarization components of an input signal into a first component signal and a second component signal such that said first component signal propagates along a first path and the second component signal propagates along a second path, wherein said first component signal reaches a location relative to when said second component reaches said location at times differing by a delayed time.

2. The apparatus of claim 1 further comprising a director at said location for directing said first component signal and said second component signal to propagate along a common path from said location.

3. The apparatus of claim 1 further comprising a receiver for receiving said first component signal and said second component signal at said location.

4. The apparatus of claim 3 wherein said receiver coherently receives said first component signal and said second component signal, thereby generating a coherence signal representative of said input signal.

5. The system of claim 4 wherein said input signal is a relatively weak signal and said coherence signal is a relatively strong signal.

6. The apparatus of claim 1 wherein said polarization beam splitter comprises a polarizing beam splitter.

7. The apparatus of claim 1 wherein said polarizing beam splitter comprises a beam splitter cube.

8. The apparatus of claim 1 wherein said polarization beam splitter comprises a magnetic material.

9. The system of claim 1 wherein at least part of said first path is in free space.

18. A method for time delaying different polarization components of a signal relative to one another, comprising:

splitting first and second polarization components of an input signal into a first component signal and a second component signal such that said first component signal propagates along a first path and the second component signal propagates along a second path, wherein said first component signal reaches a location relative to when said second component reaches said location at times differing by a delayed time.

19. The method of claim 18 further comprising directing said first component signal and said second component signal to propagate along a common path from said location.

20. The method of claim 18 further comprising receiving said first component signal and said second component signal at said location in a receiver.

21. The method of claim 20 further comprising coherently receiving said first component signal and said second component signal in said receiver, thereby generating a coherence signal representative of said input signal.

22. The method of claim 21 wherein said input signal is a relatively weak signal and said coherence signal is a relatively strong signal.

23. The method of claim 18 wherein said polarization beam splitter comprises a polarizing beam splitter.

24. The method of claim 18 wherein said polarizing beam splitter comprises a beam splitter cube.

25. The method of claim 18 wherein said polarization beam splitter comprises a magnetic material.

26. The method of claim 18 wherein at least part of said first path is in free space.

27. The method of claim 18 wherein at least part of said first path is defined by an optical fiber.

relative phase difference between time-separated components of an electromagnetic signal, comprising:

a polarization splitter for splitting a quantum signal into components of different polarization; and

means providing for recombination of said components after providing a relative time delay to at least one of the components.

37. The apparatus of claim 36 further comprising means for changing the phase of electromagnetic field of at least one of said components.

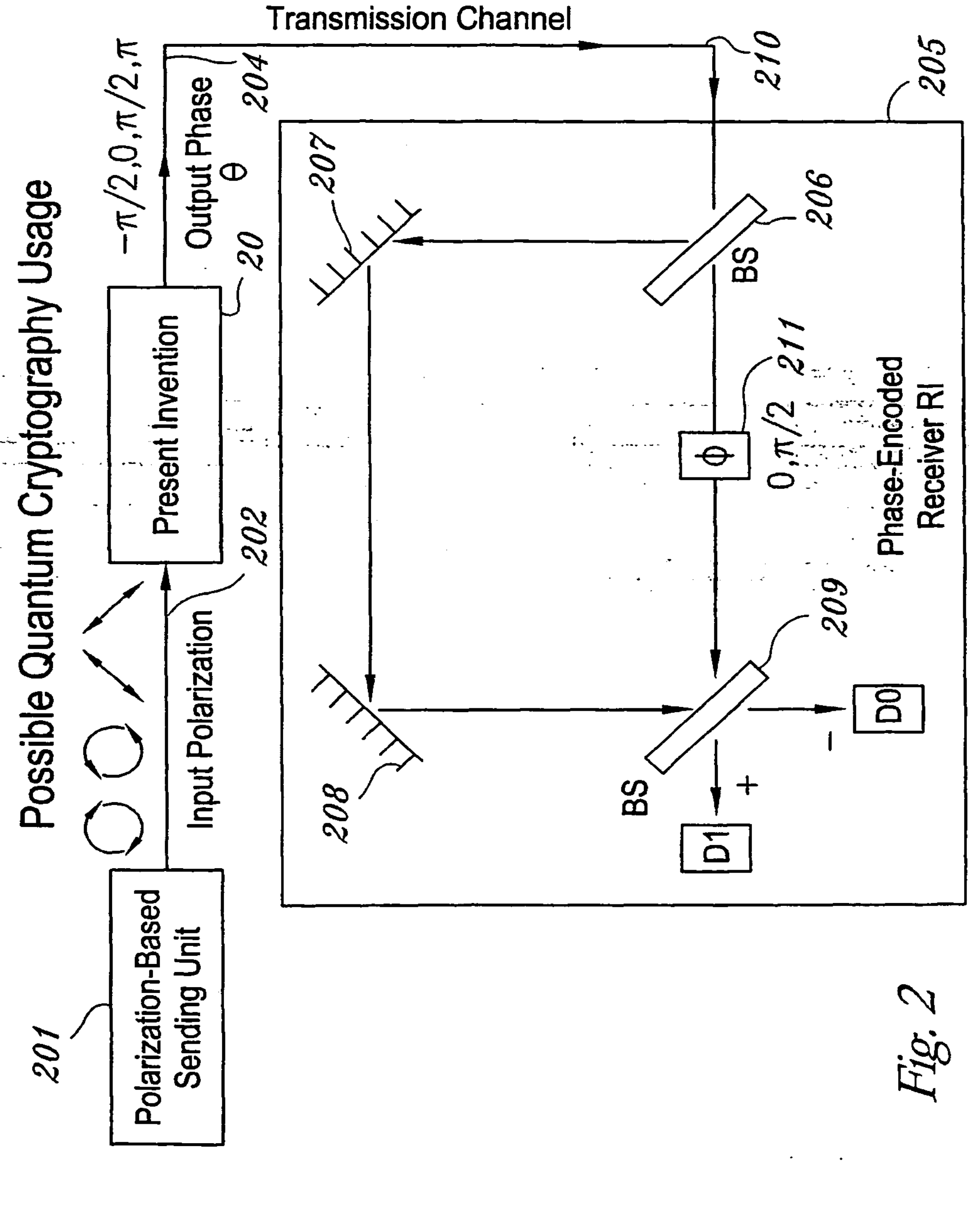
Possible Quantum Cryptography Usage
Polarization-Based Sending Unit
201
Input Polarization
202
Present Invention
20
Output Phase
θ
204
−π/2,0,π/2,π
Transmission Channel
210
205
BS
206
207
ϕ
0,π/2
211
Phase-Encoded Receiver RI
BS
209
208
D0
D1
+
−

Fig. 2

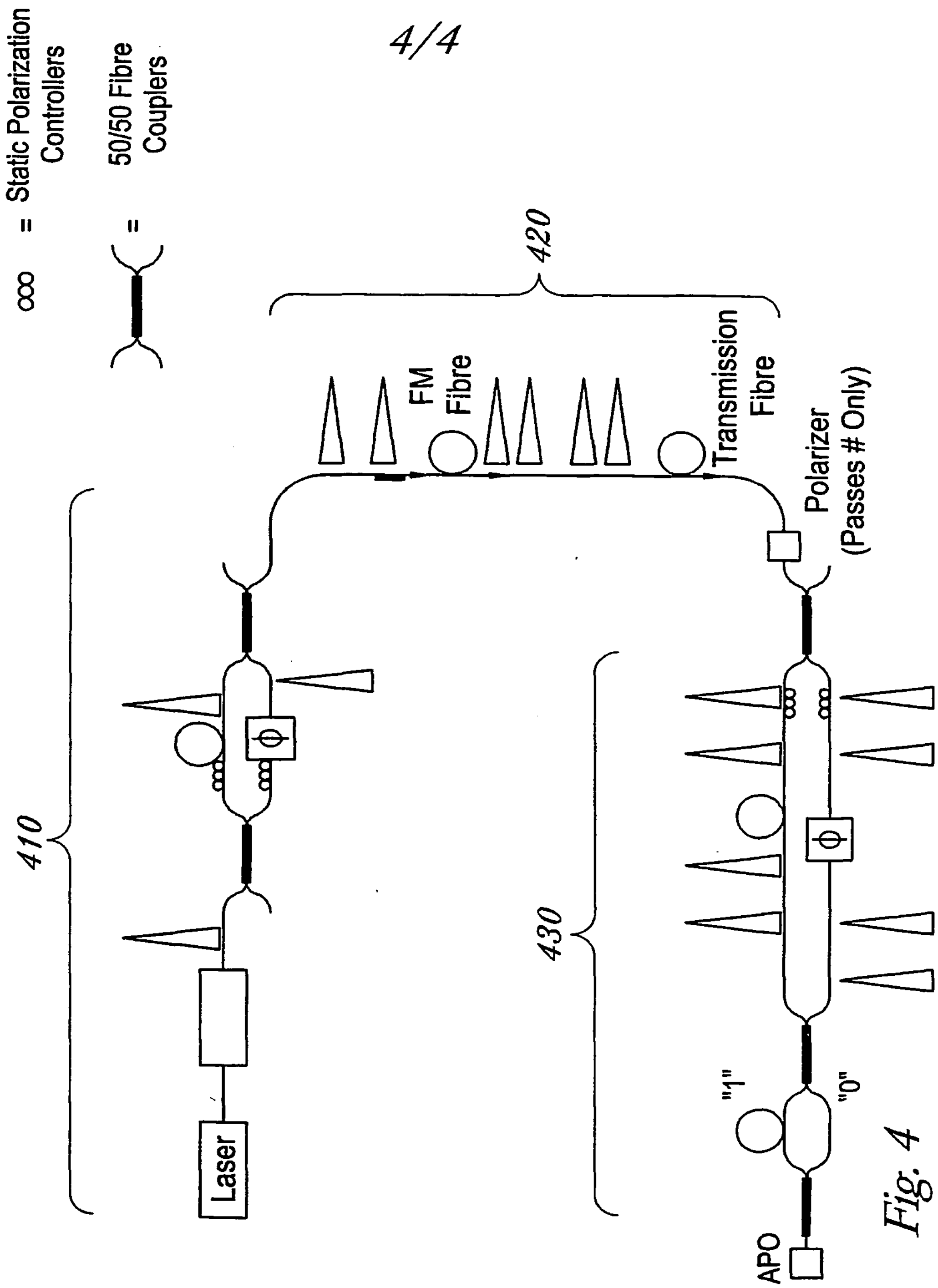
= Static Polarization Controllers
= 50/50 Fibre Couplers
420
FM Fibre
Transmission Fibre
Polarizer (Passes # Only)
410
Laser
430
"1"
"0"
APO

Fig. 4

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 October 2002 (24.10.2002)

PCT

(10) International Publication Number
WO 02/084337 A3

(51) International Patent Classification[7]: H04L 9/00

(21) International Application Number: PCT/US02/08251

(22) International Filing Date: 10 April 2002 (10.04.2002)

(25) Filing Language: English

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(30) Priority Data:
60/283,017 11 April 2001 (11.04.2001) US

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(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(88) Date of publication of the international search report: 10 April 2003

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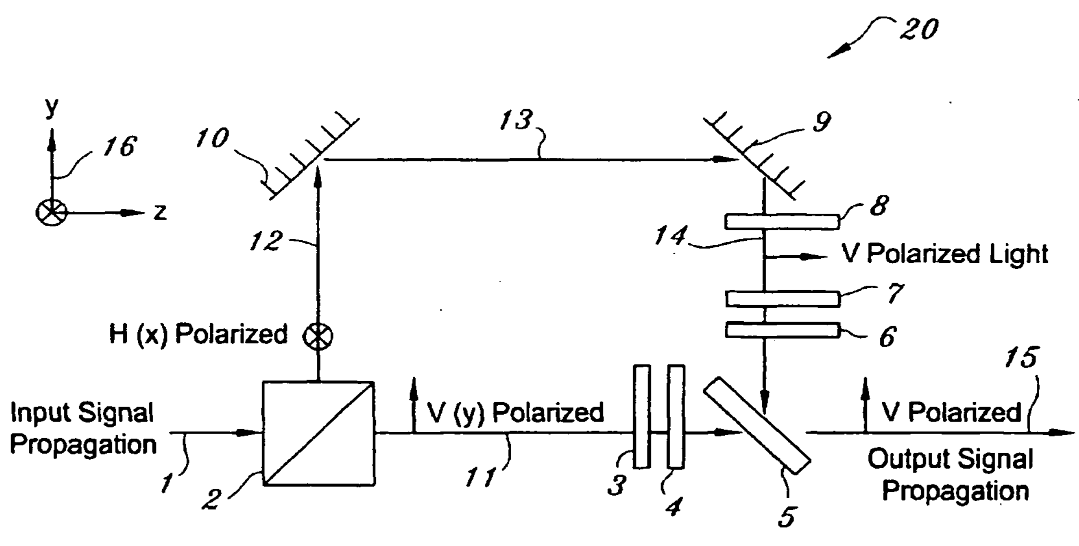
(54) Title: POLARIZATION TO PHASE CONVERTER



(57) Abstract: The invention provides an apparatus and method for time delaying different polarization components of a signal (1) relative to one another, comprising a polarization signal splitter (2) which splits first and second polarization components of an input signal into a first component signal (11) and a second component signal (12) such that said first component signal propagates along a first path and the second component signal propagates along a second path, wherein said first component signal reaches a location (5) relative to when said second component reaches said location at times differing by a delayed time, and use of the apparatus in a communication system. The apparatus may be used for quantum cryptography, to convert a sender's polarization-qubit signal into a signal appropriate for channels and receivers based on phase-encoded schemes.

WO 02/084337 A3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/08251

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : H04L 9/00
US CL : 380/278
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 380/278

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,188,768 B1 (BETHUNE et al.) 13 February 2001 (13.02.2001), abstract, all figures.	1-37
A, E	US 6,438,234 B1 (GISIN et al.) 20 August 2002 (20.08.2002), abstract.	1-37
A, P	US 6,272,224 B1 (MAZOURENKO et al.) 07 August 2001(07.08.2001), abstract.	1-37
A	US 5,999,285 A (BRANDT et al.) 07 December 1999 (07.12.1999), abstract.	1-37
A	US 5,953,421 A (TOWNSEND) 14 September 1999 (14.09.1999), abstract.	1-37
A	US 5,850,441 A (TOWNSEND et al.) 15 December 1998 (15.12.1998), abstract.	1-37
A	US 5,768,378 A (TOWNSEND et al.) 16 June 1998 (16.06.1998), abstract.	1-37
A	US 5,764,765 A (PHOENIX et al.) 09 June 1998 (09.06.1998), abstract.	1-37
A	US 5,757,912 A (BLOW) 26 May 1998 (26.05.1998), abstract.	1-37

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
01 October 2002 (01.10.2002)	12 DEC 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Gilberto Barrón Telephone No. (703) 305-3900